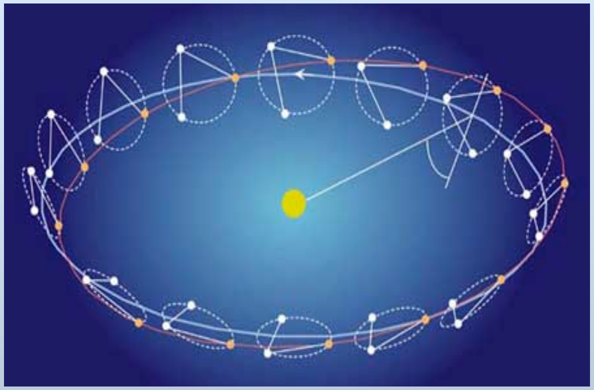
Time Delay Interferometry using the UF LISA Benchtop Simulator

Rachel J. Cruz

6th International LISA Symposium June 21, 2006

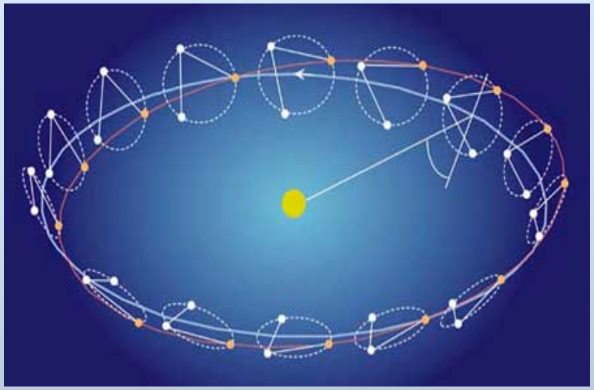
Laser Phase Noise



LISA needs to be able to see length changes of ~10 pm corresponding to a required frequency stability of less than **6×10^{-7} Hz/√Hz**.

- Pre-stabilization
  - Reference cavity
- Arm-locking
  - Use the LISA arm as a stable reference
- Time Delay Interferometry (TDI)

Laser Phase Noise



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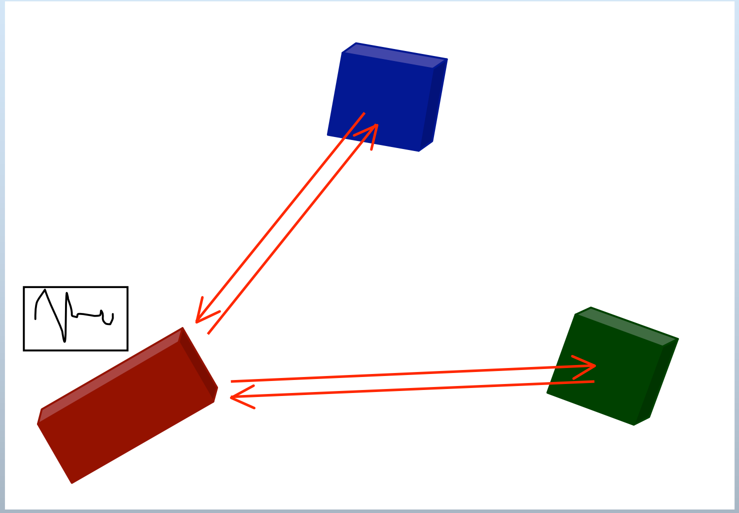
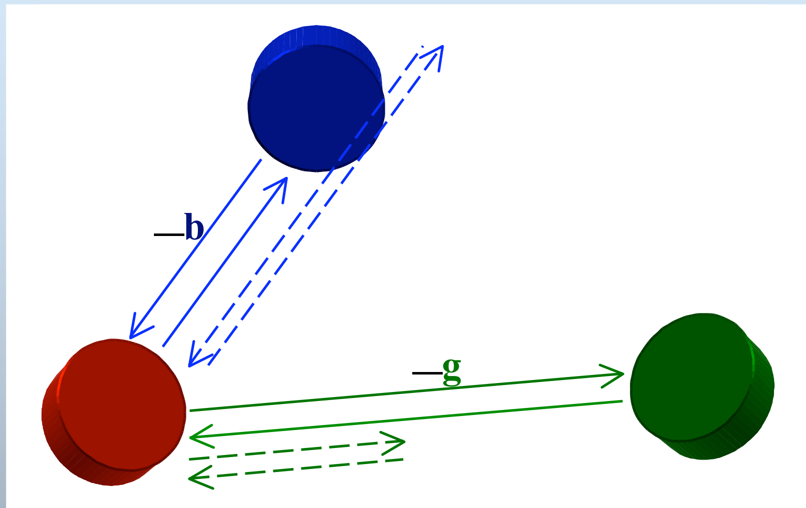
Ira Thorpe- LISA System & Technology Session Friday morning

Time Delay Interferometry



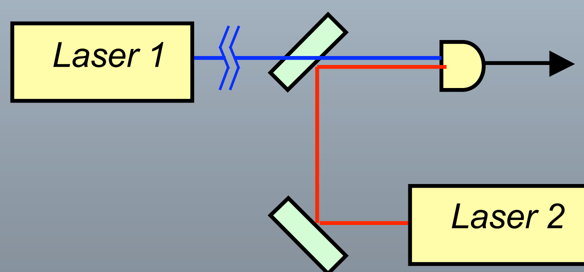
Time Delay Interferometry



First Generation X-combination:

$S_{b}(t) - S_{g}(t) - S_{b}(t- 2\_{g}) + S_{g}(t- 2\_{b})$

cancels laser phase noise

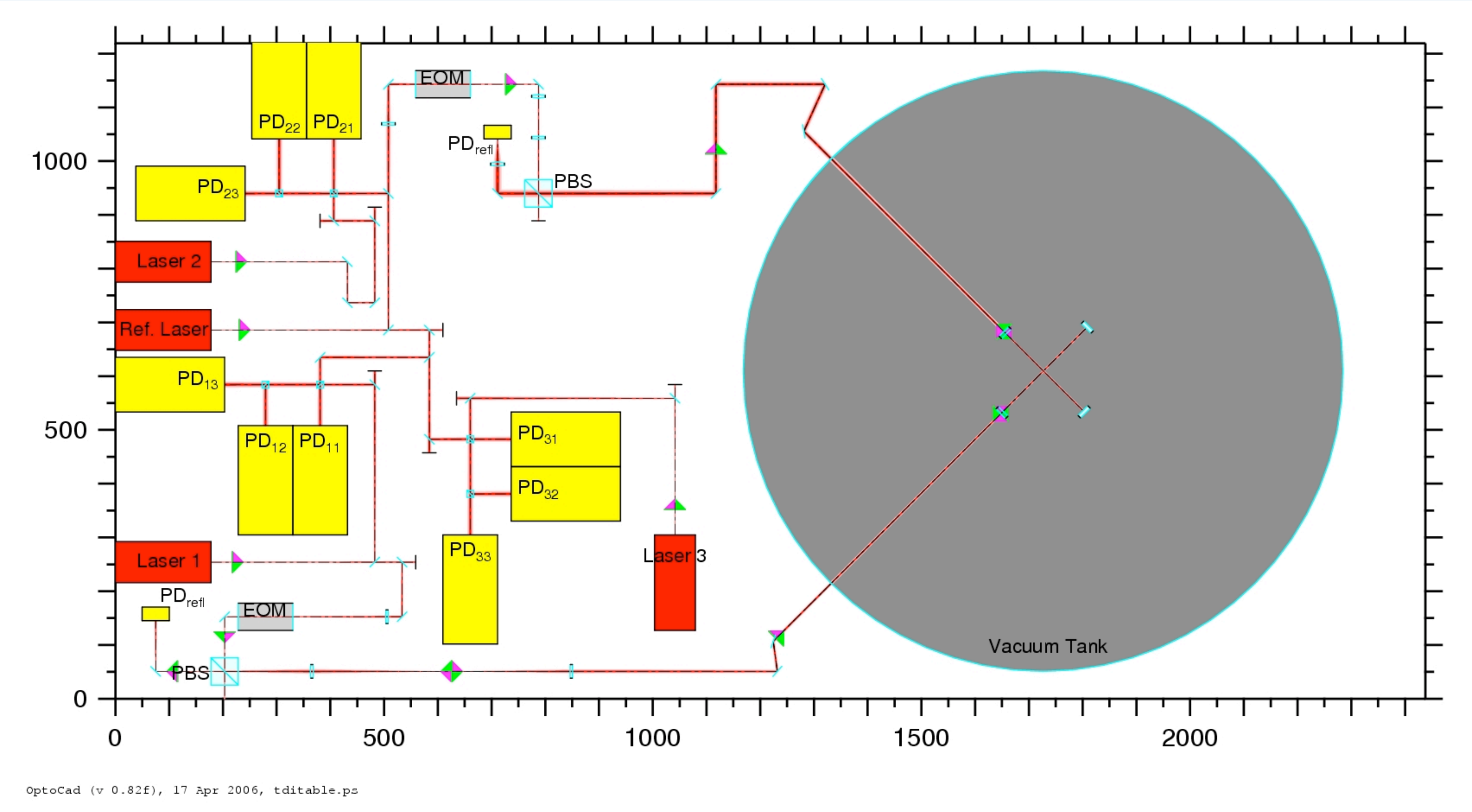


$= S(t)$

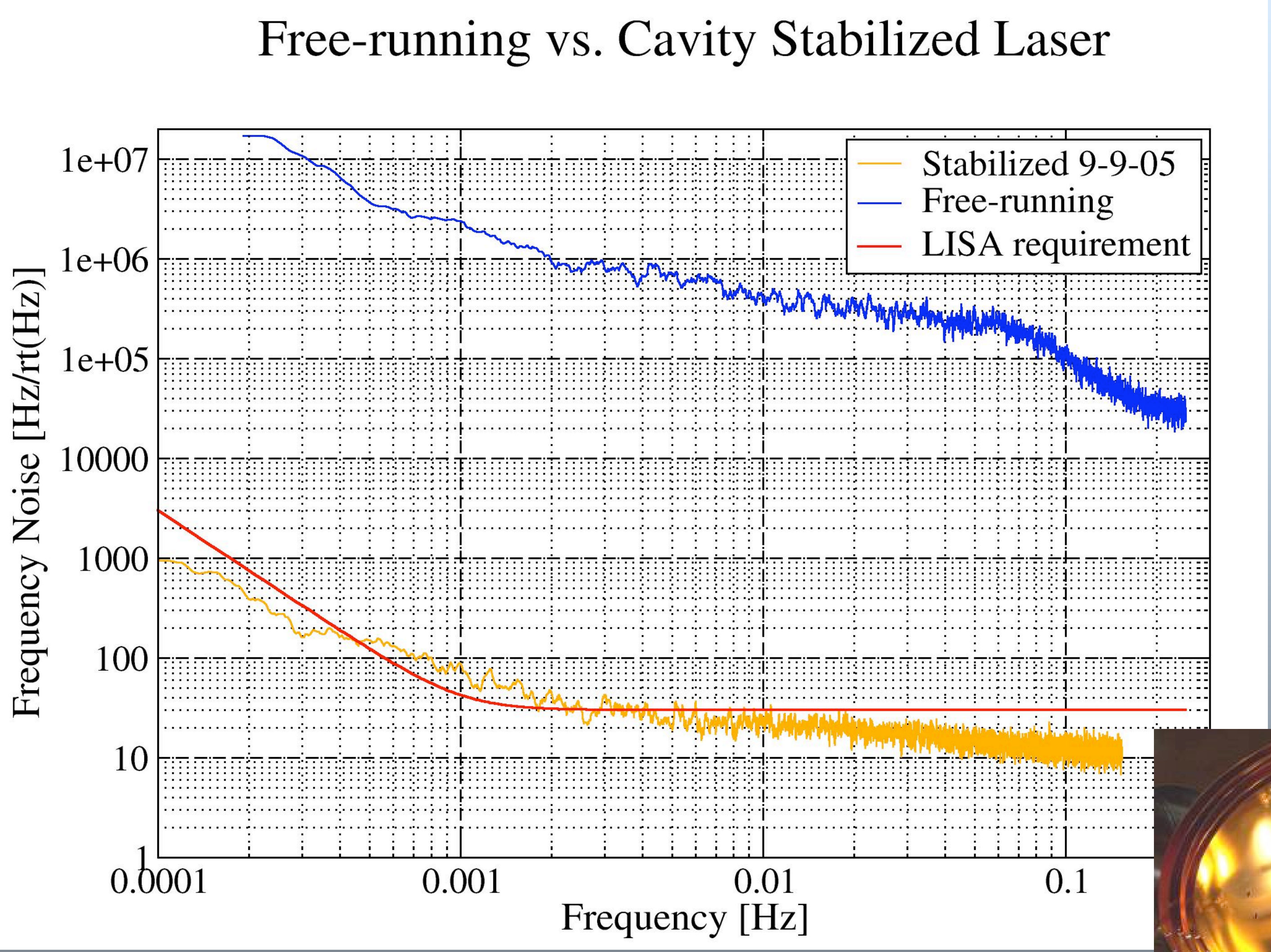
Additional terms can be added to compensate for transponder noise, bench noise, and spacecraft motion

UF LISA Benchtop Simulator

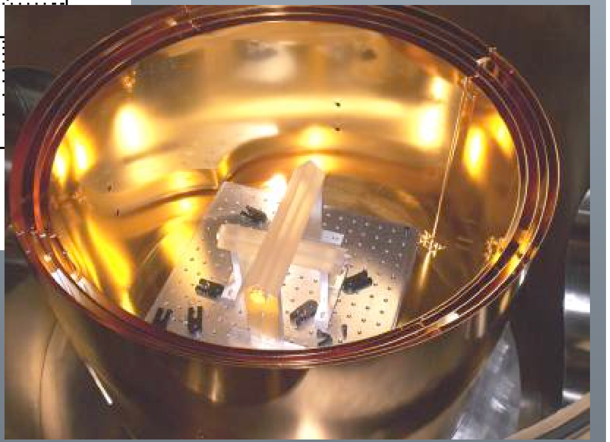
Our goal is to create a facility to investigate experimentally aspects of LISA. Currently, we are looking at TDI, arm-locking, laser communication, and material and bond stability studies.



Laser frequency stabilization



Two Zerodur spacers with optically-contacted mirrors

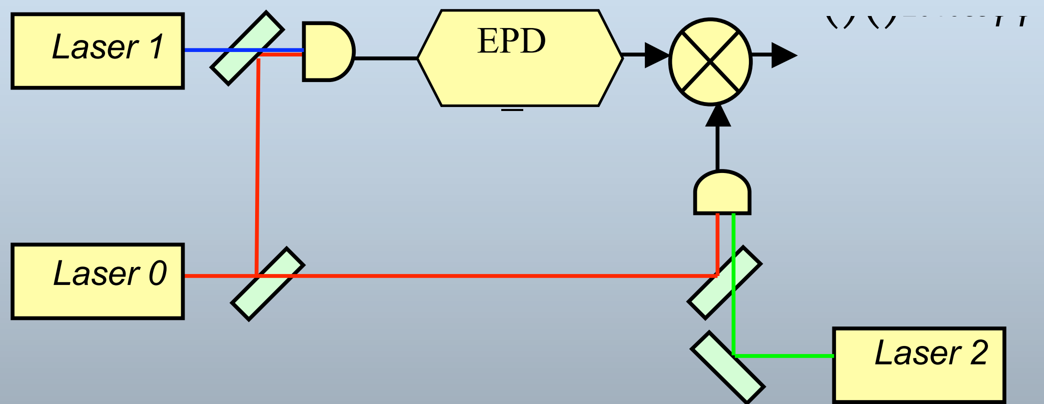


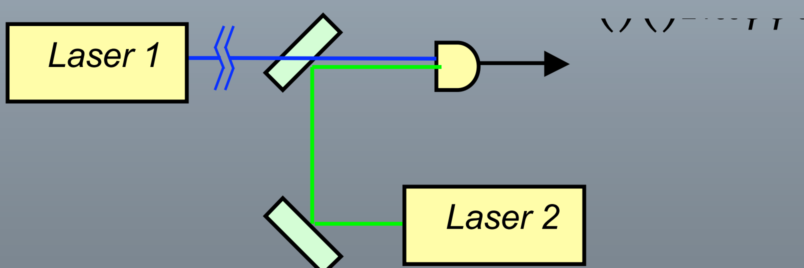
Electronic Phase Delay

We delay the optical signals electronically to create the long LISA arm in the lab.

<u>EPD</u>

- Beat note is electronically delayed
- Reference laser is required

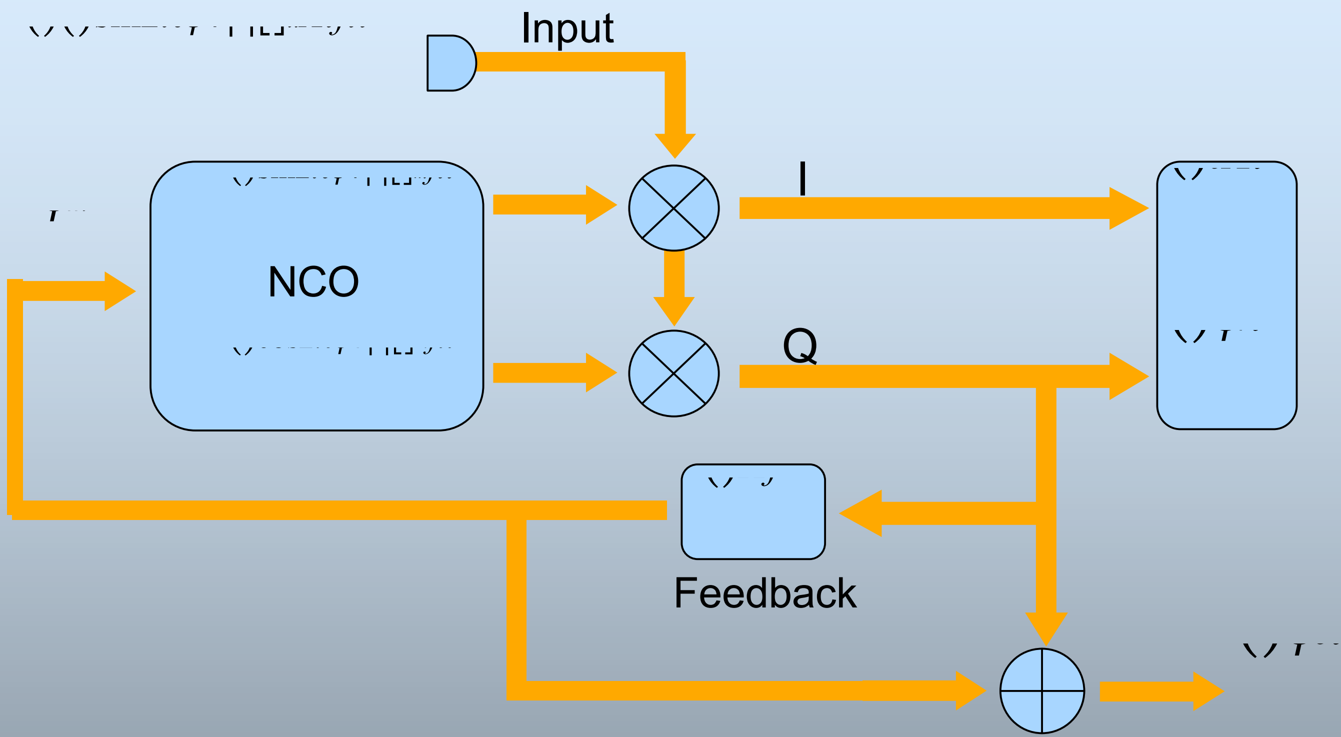




<u>LISA</u>

- LISA arm delays phase of light
- Beat note formed with 2nd laser

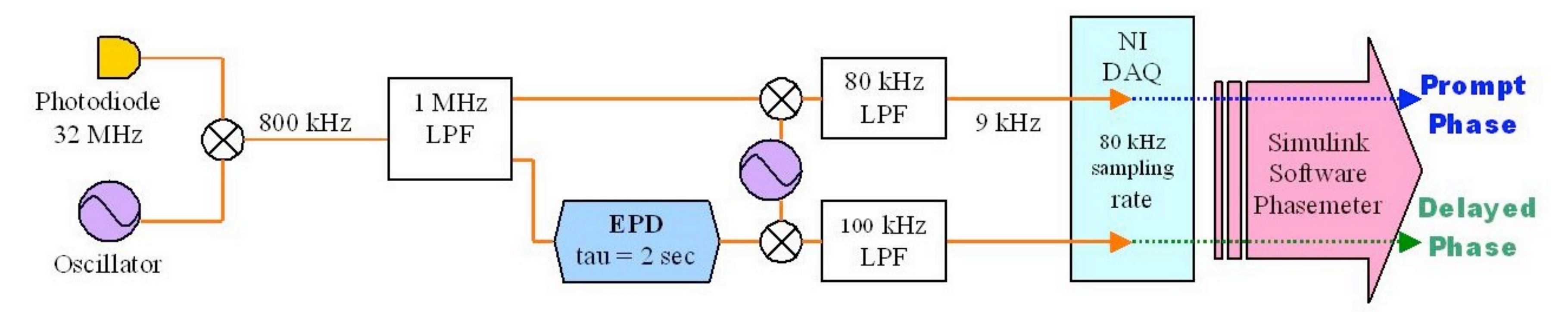
LISA-like Post-process Phasemeter

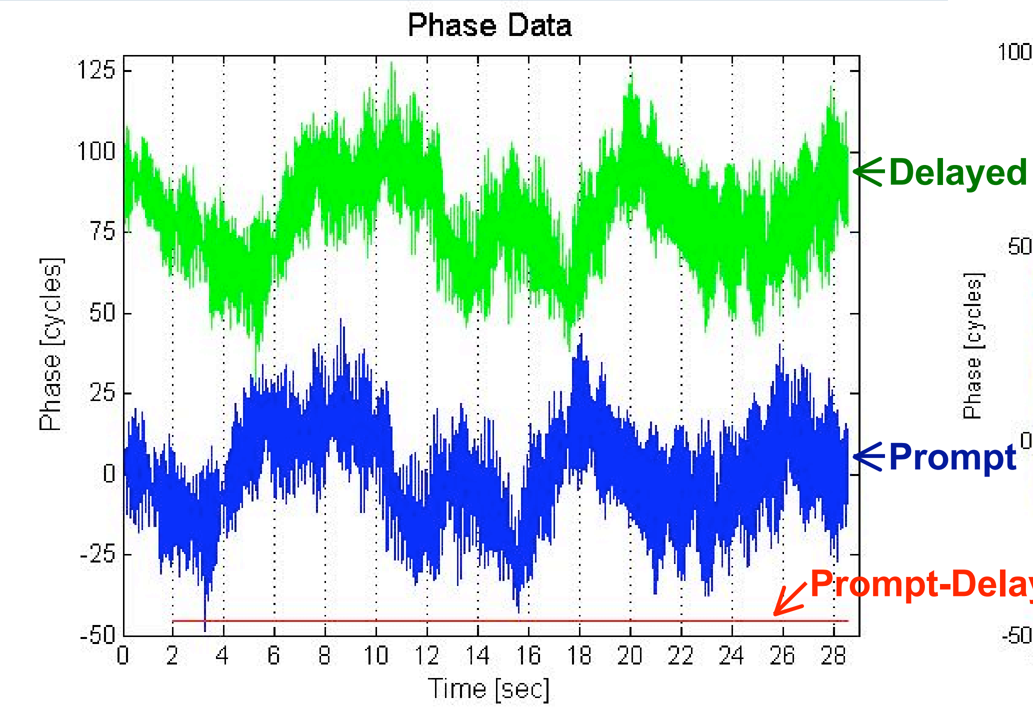


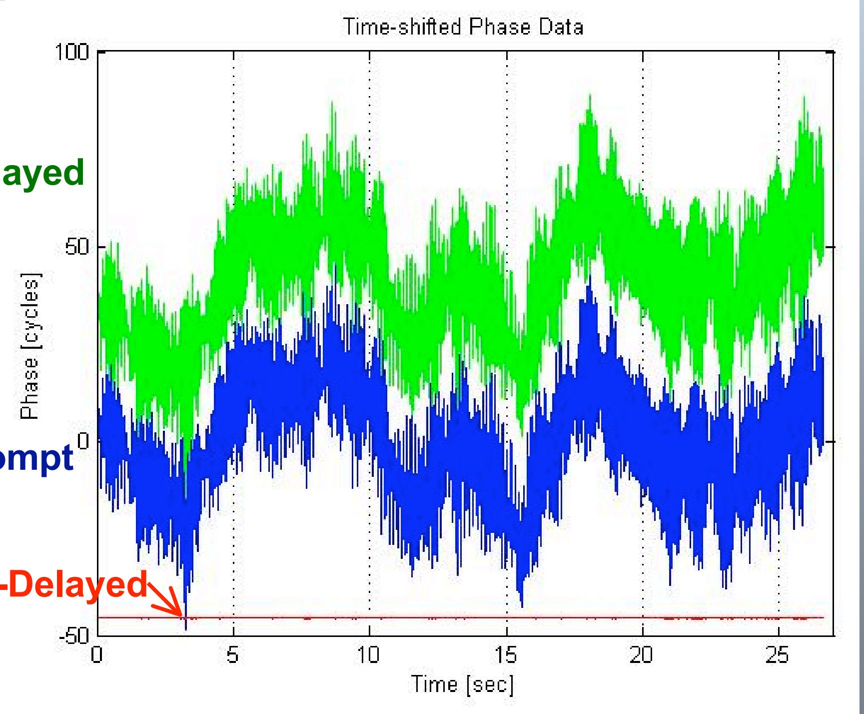
I used a post-process/software version in Simulink

- requires 10 kHz signals ◊ demodulation stage in experiment
- requires sampling at 80 kHz ◊ limits data runs to roughly a minute

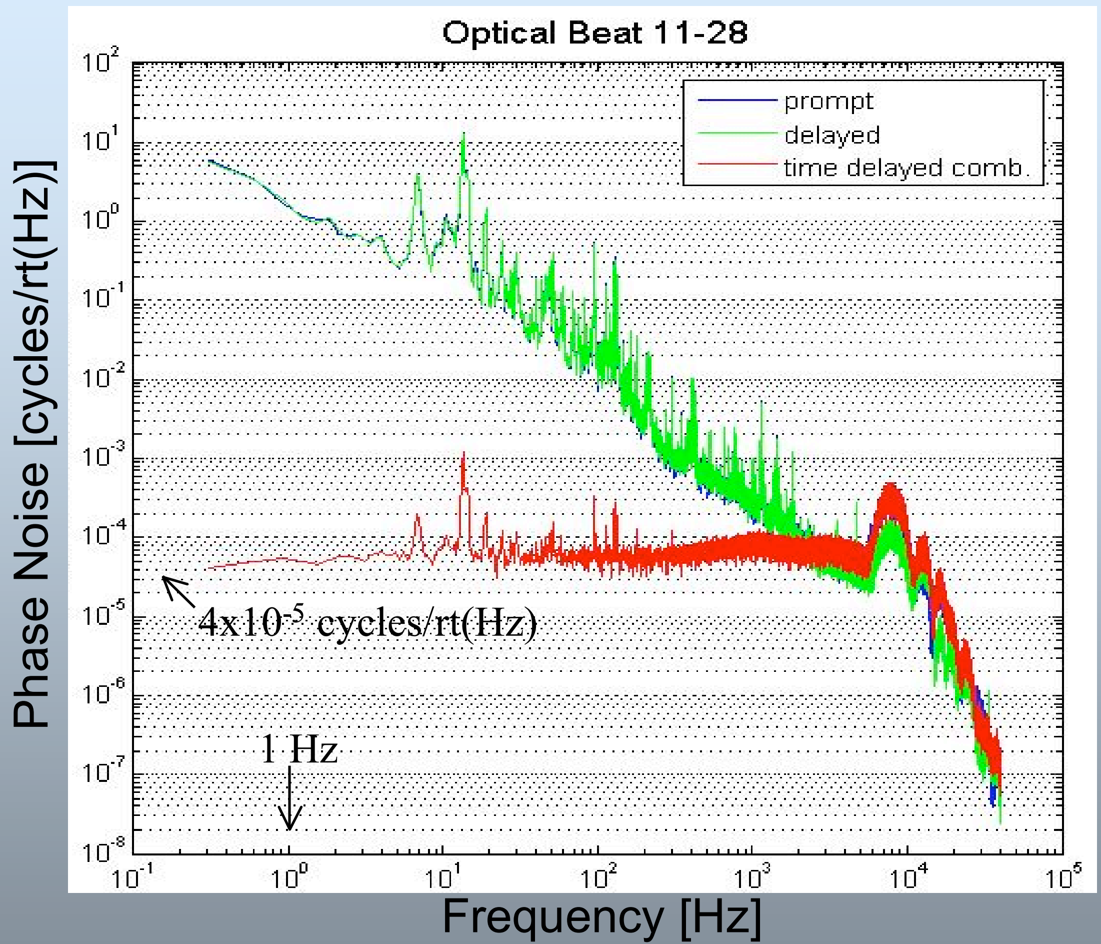
Initial Optical Experiment







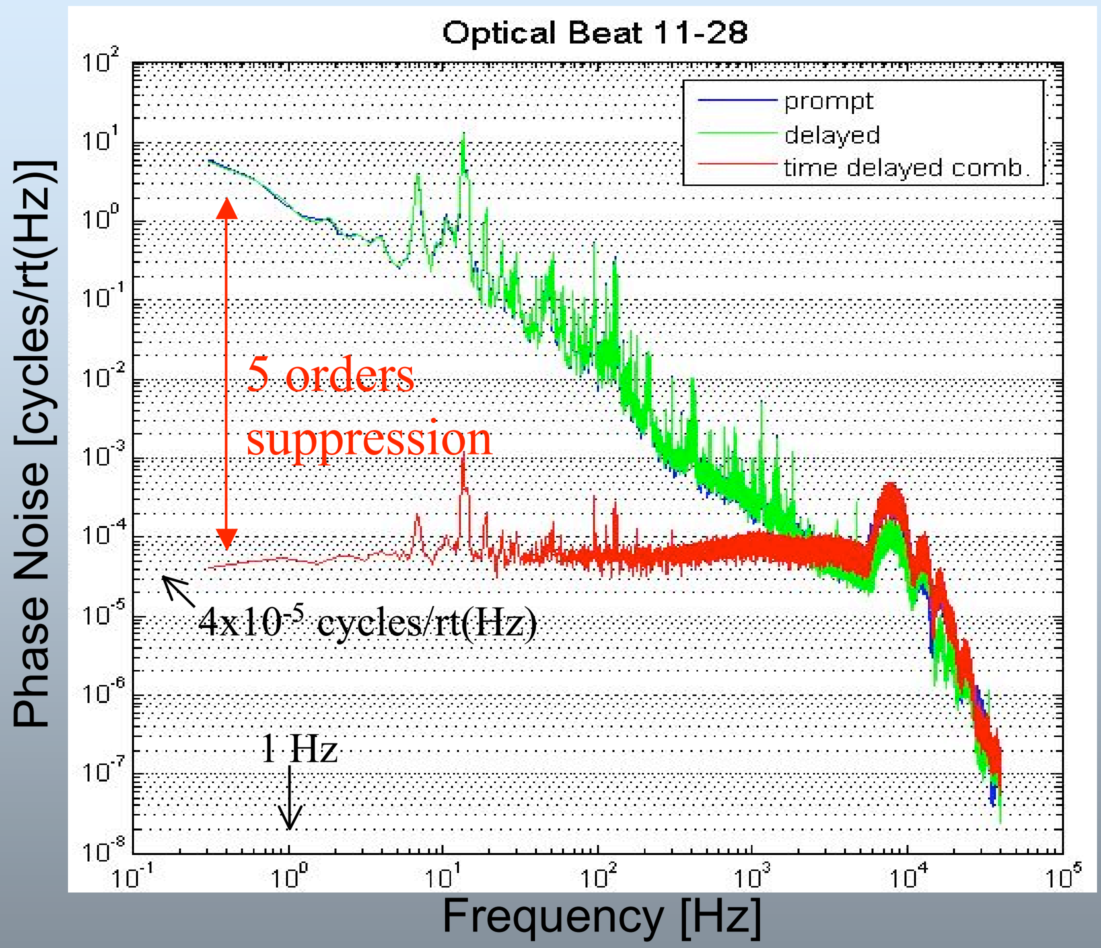
Initial Optical Experiment Results



Frequency range currently limited by sampling of post-process phasemeter.

We are less than an order of magnitude from LISA requirements!

Initial Optical Experiment Results



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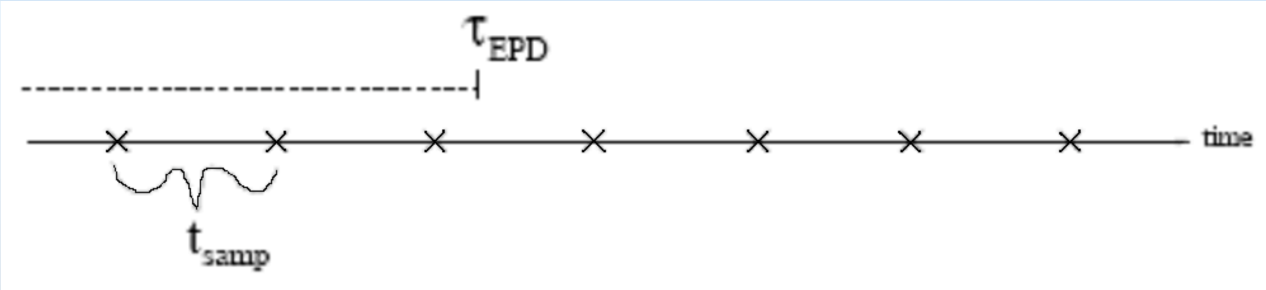
Timing Error



The delay time of the EPD, just as the optical delay time of the LISA arm, will not fall exactly at one of the sampling points of the data stream.

Define the timing error as: $\Delta\tau = |\tau_{EPD} - \tau_{shift}|$

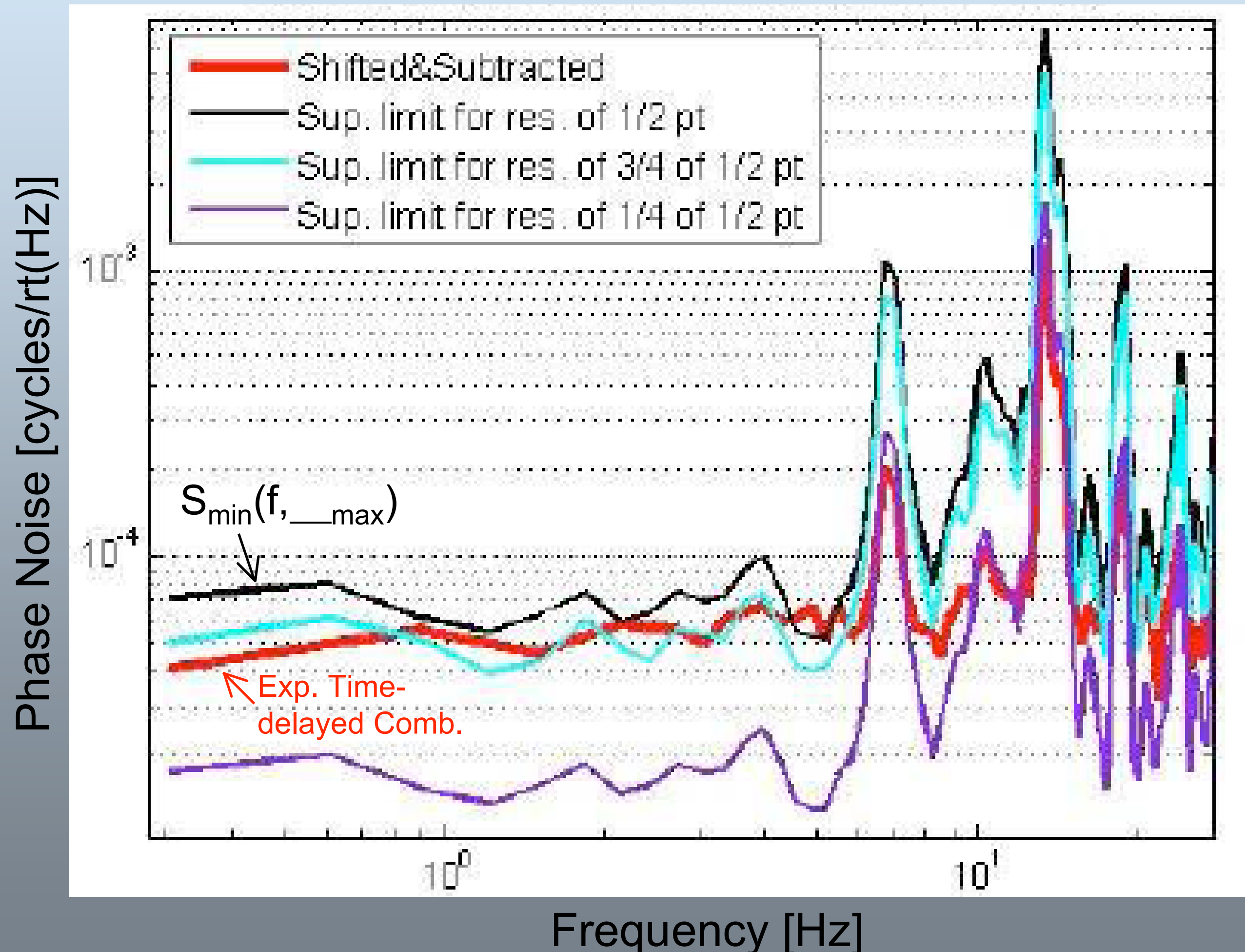
$$\Delta\tau_{\max} = \frac{1}{2} t_{samp}$$

Suppression limits due to timing error

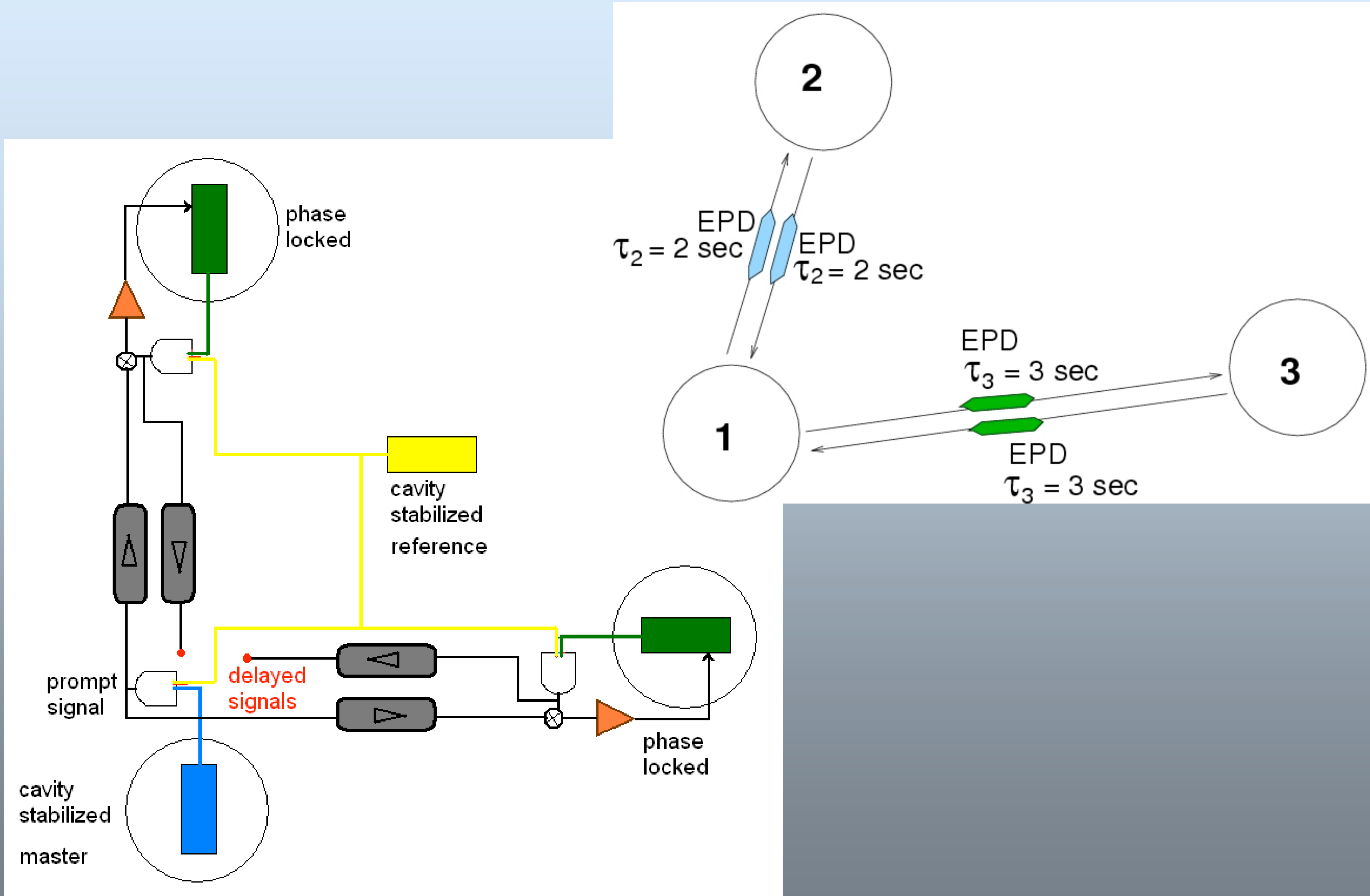
$$S(t) = \phi_p(t) - \phi_p(t - \Delta\tau)$$

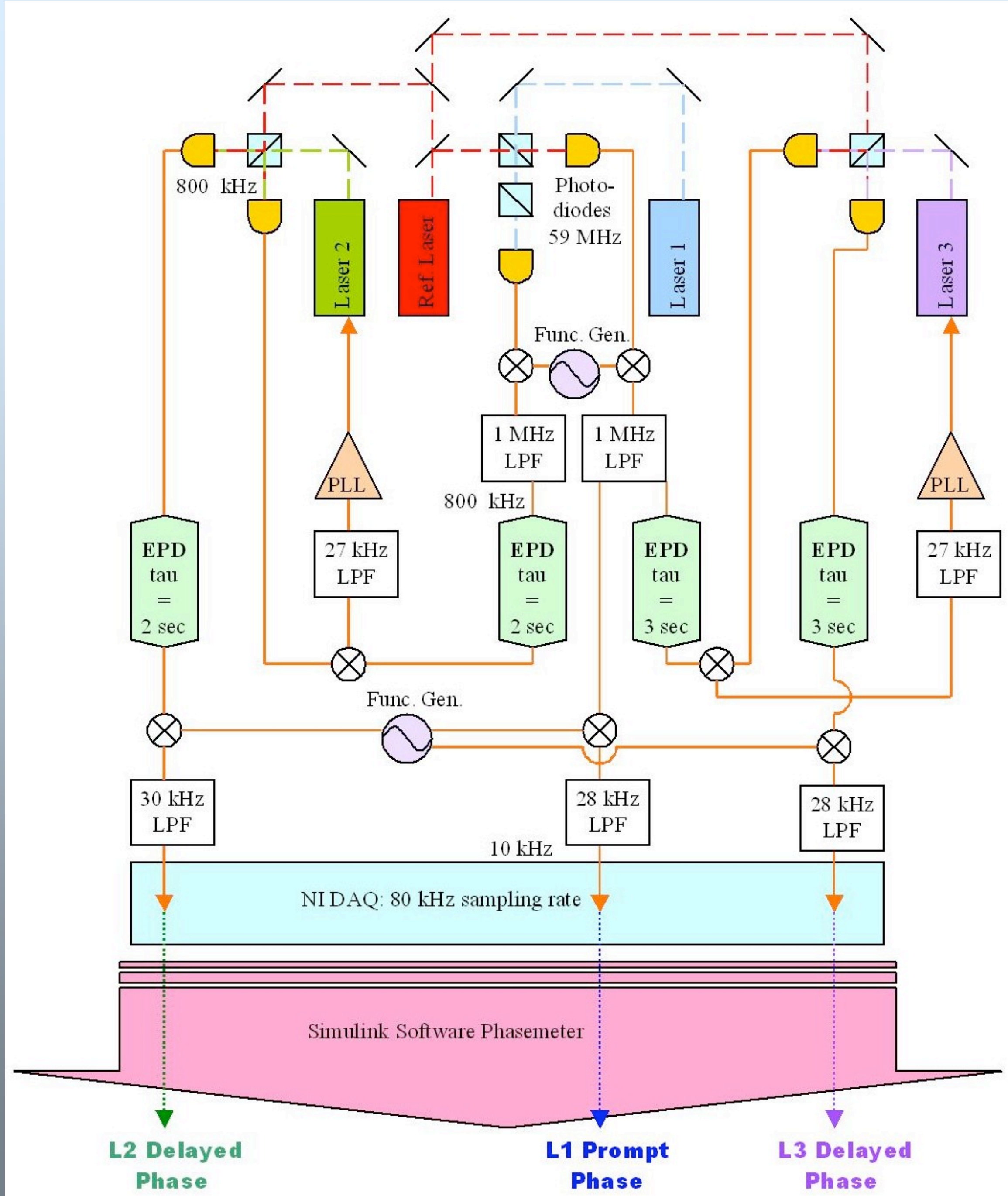
$$|\tilde{S}_{\min}(f, \Delta\tau)| = 2\sin(\pi f \Delta\tau)|\tilde{\phi}_p(f)|$$

- The timing error in the experiment < ___$_{max}$ = _ t_{samp} = 6.25 _sec
- Interpolation can be used to reduce the timing error
- Experimental results appear to hit another noise source at ~$5\text{x}10^{-5}$ cycles/rt(Hz)



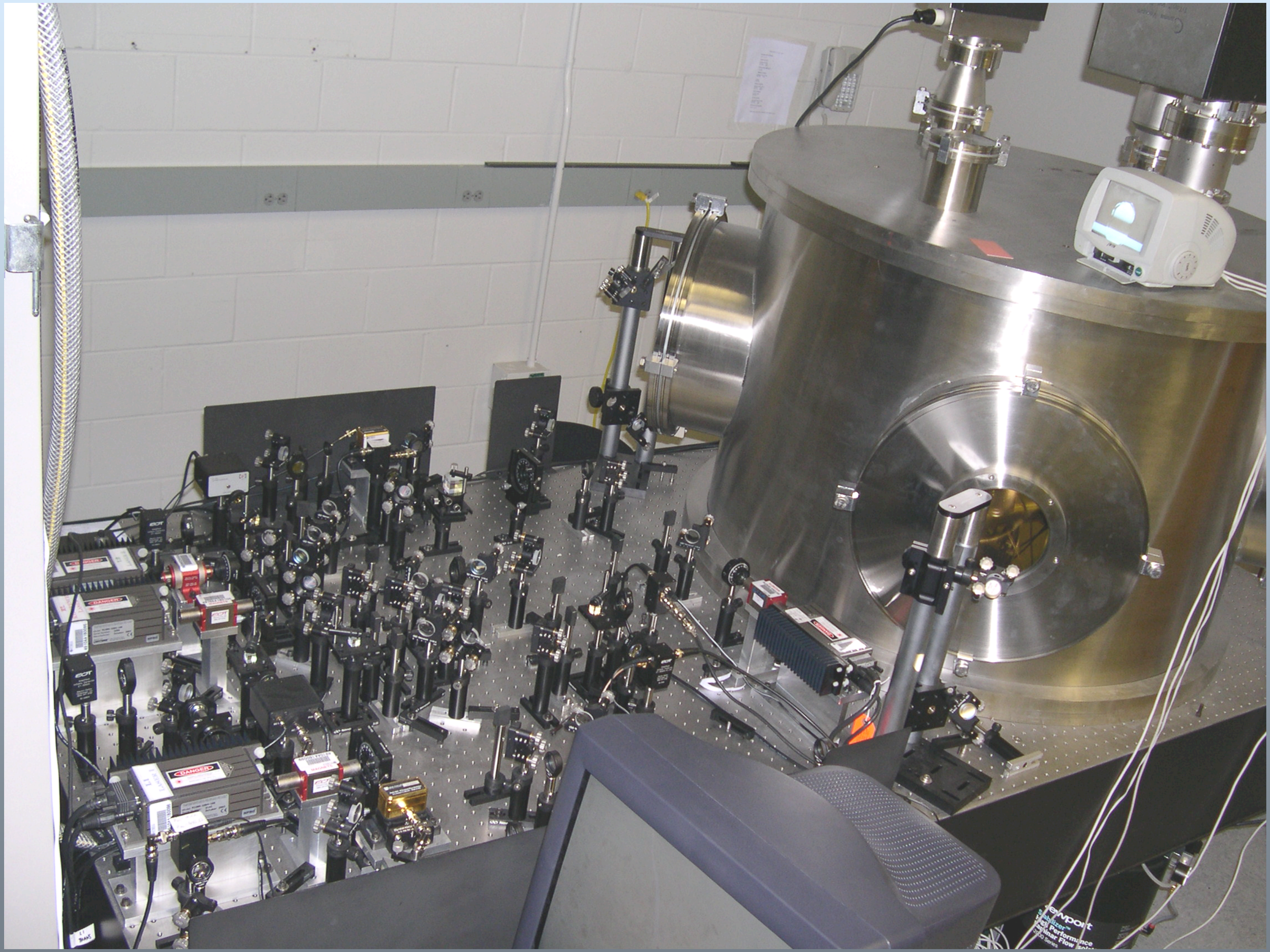
Two-Arm Experiment





800 kHz
Laser 2
Ref Laser
Photo-
diodes
59 MHz
Laser 1
Laser 3
Func. Gen.
1 MHz
LPF
1 MHz
LPF
PLL
PLL
800 kHz
EPD
tau
=
2 sec
27 kHz
LPF
EPD
tau
=
2 sec
EPD
tau
=
3 sec
EPD
tau
=
3 sec
27 kHz
LPF
Func. Gen.
30 kHz
LPF
28 kHz
LPF
28 kHz
LPF
10 kHz
NI DAQ: 80 kHz sampling rate
Simulink Software Phasemeter
L2 Delayed
Phase
L1 Prompt
Phase
L3 Delayed
Phase

Benchtop Simulator during Two-Arm Experiment



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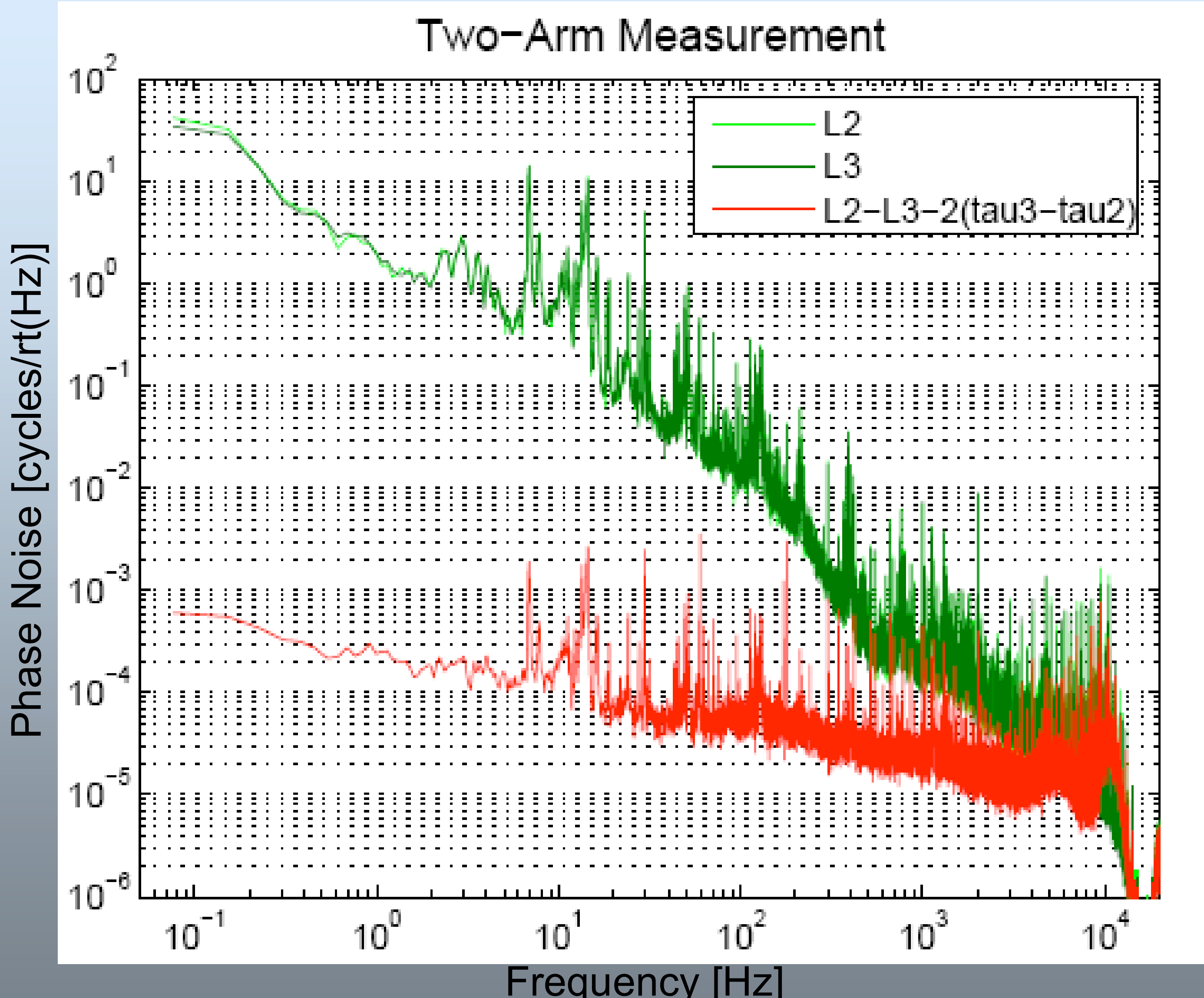

Results currently limited by PLL performance

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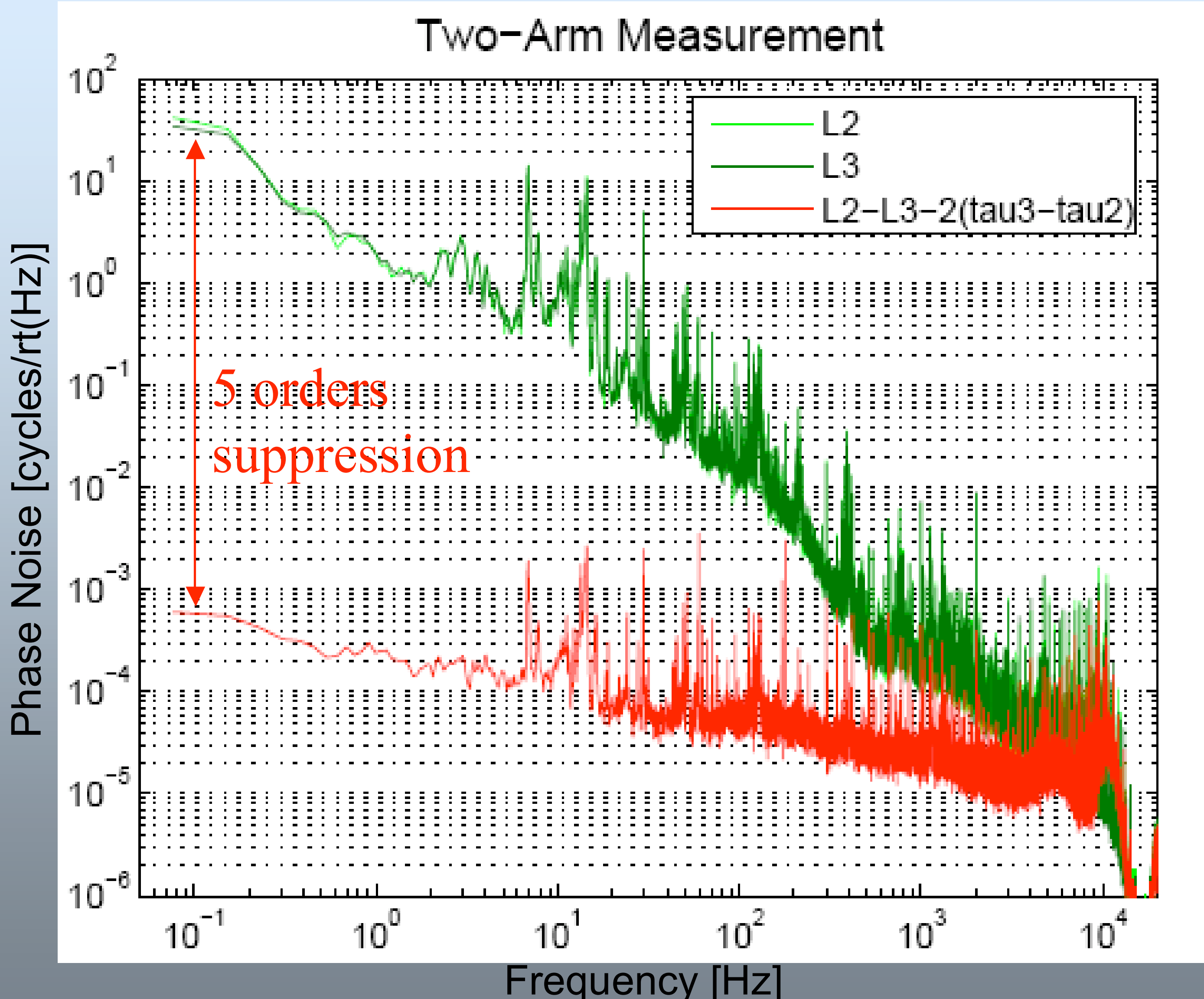

Results currently limited by PLL performance

Summary & Outlook

- One Signal experiment:
  - Less than one order of magnitude above LISA requirement @ 100 mHz
- Two-arm TDI experiment:
  - 5 orders of magnitude noise suppression @100 mHz
  - Less than 2 orders of mag above LISA requirements
  - Limited by Phase lock loops
- Real Time phasemeter under development
  - Allows long data runs to get into the LISA band
  - Develop interpolation techniques
  - Enables Noise hunting
- Build-up full LISA simulator
  - With GW, Doppler shifts, Clock noise, split OPL…

www.phys.ufl.edu/research/lisa/

The UF LISA Team:

Guido Mueller, David Tanner, Sergei Klimenko,
Ira Thorpe, Michael Hartman, Rodrigo Delgadillo,
Shawn Mitryk, Aaron Worley, Gabriel Boothe,
Sridhar Reddy, Alix Preston, and Yinan Yu

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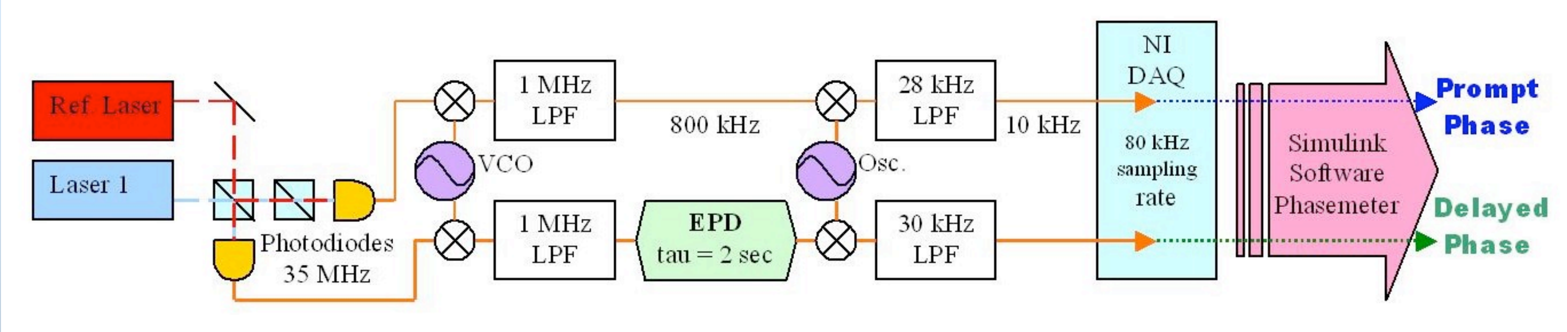
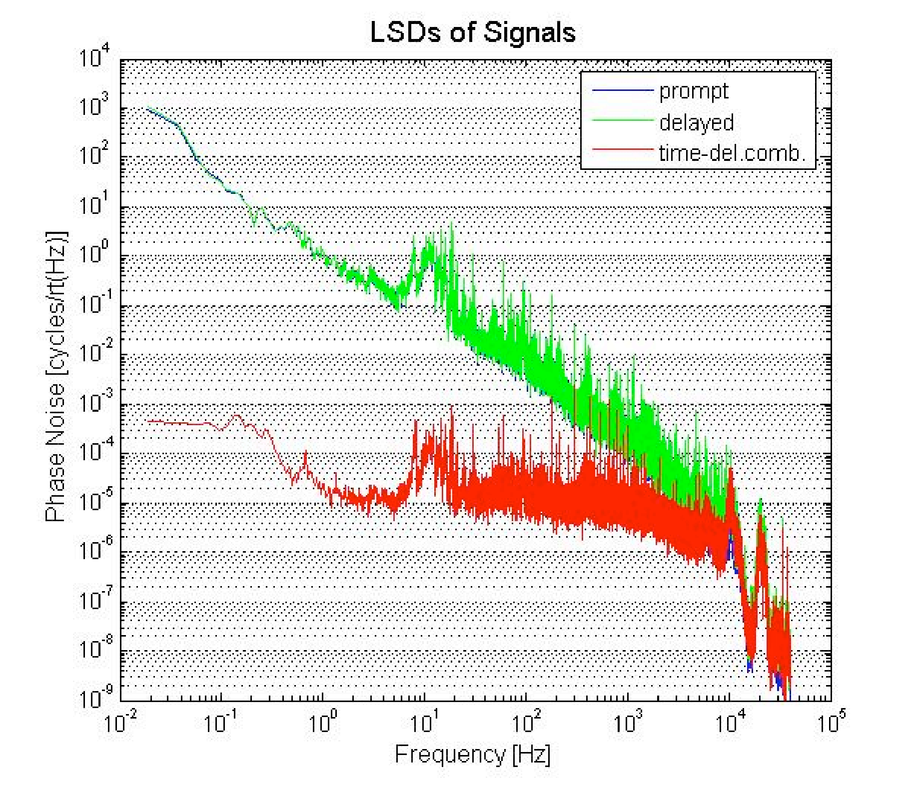
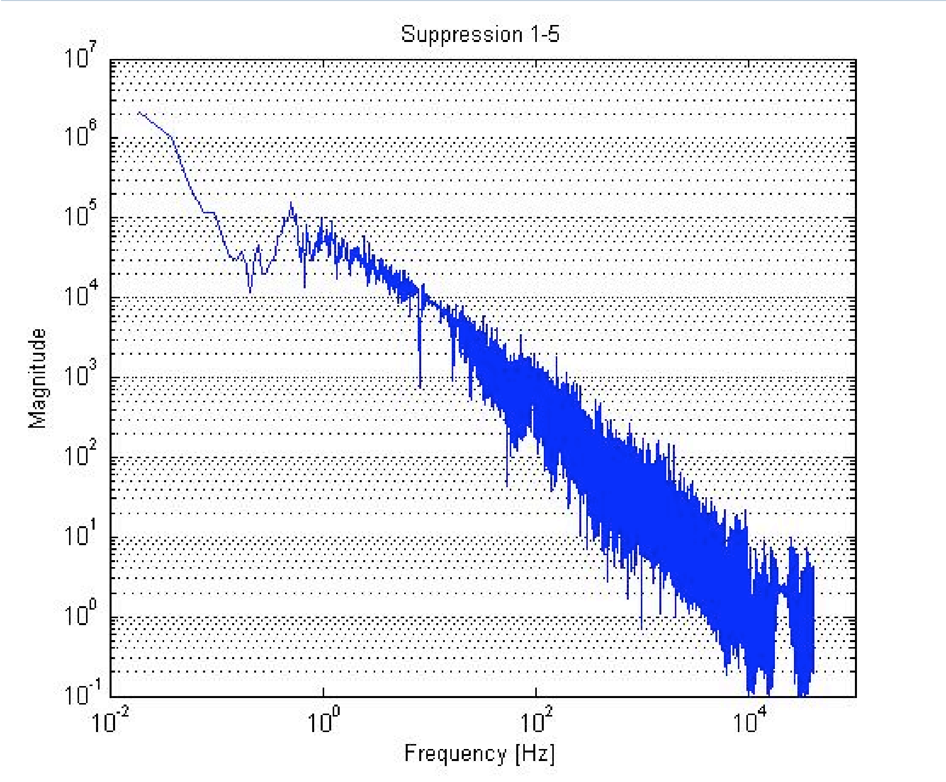
NASA Harriett G. Jenkins
Predoctoral Fellowship Program

Optically-split Experiment







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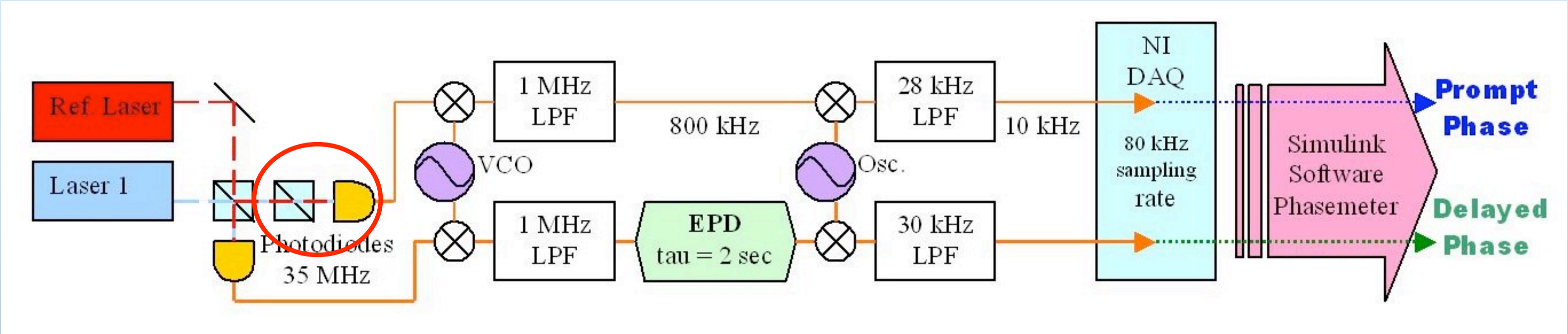

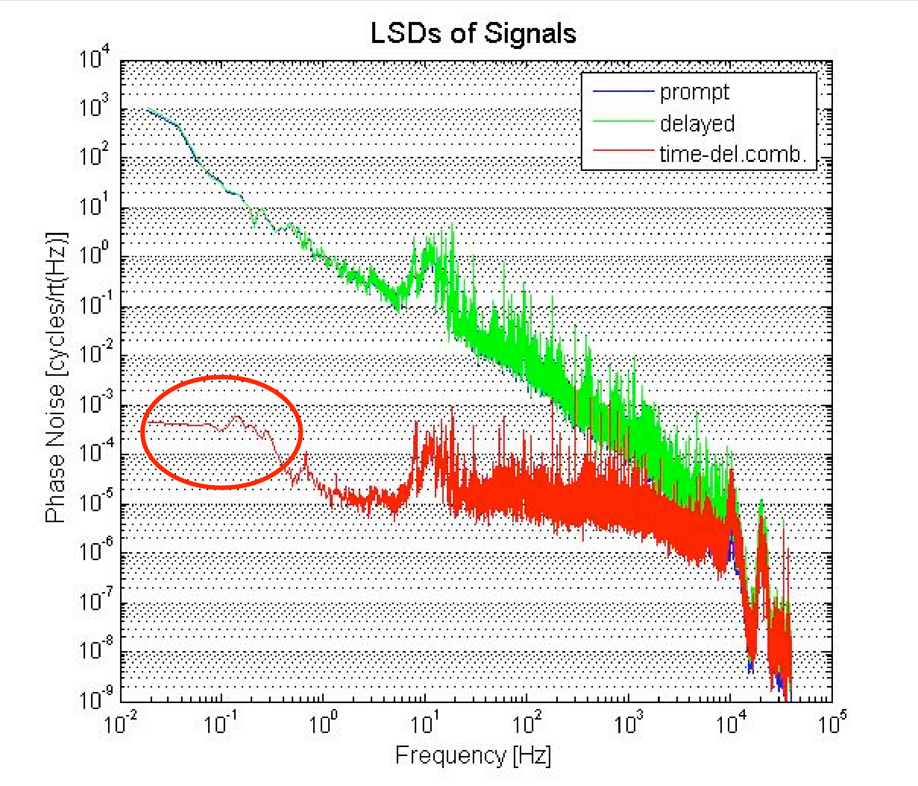

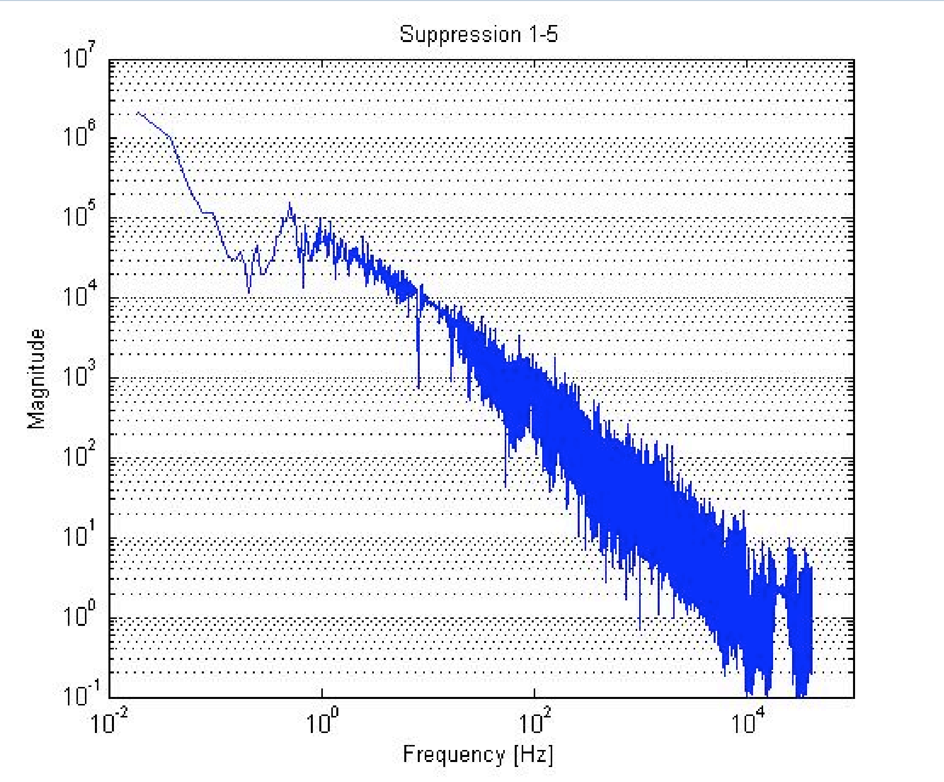

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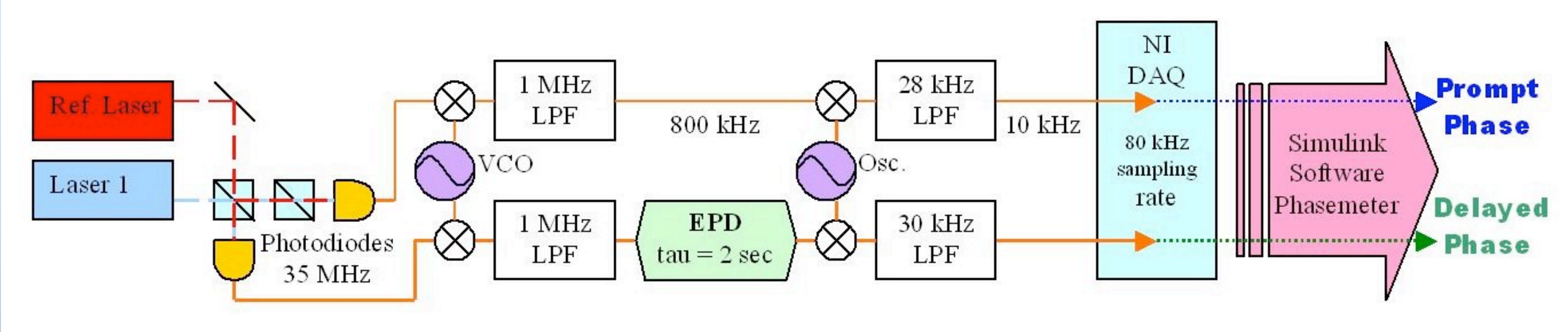
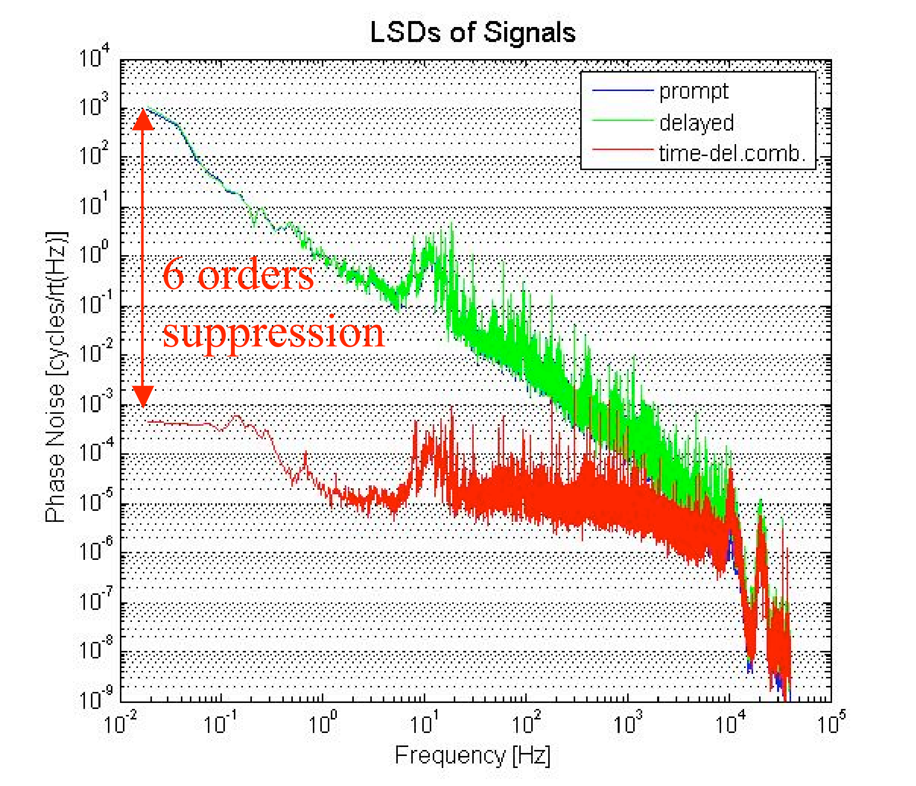
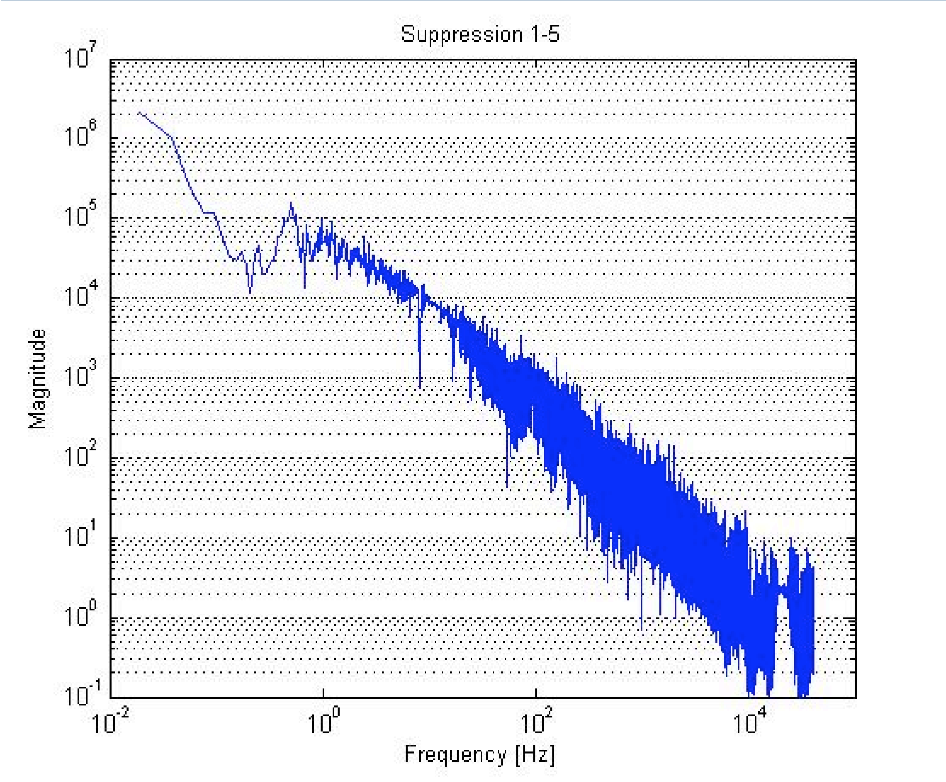


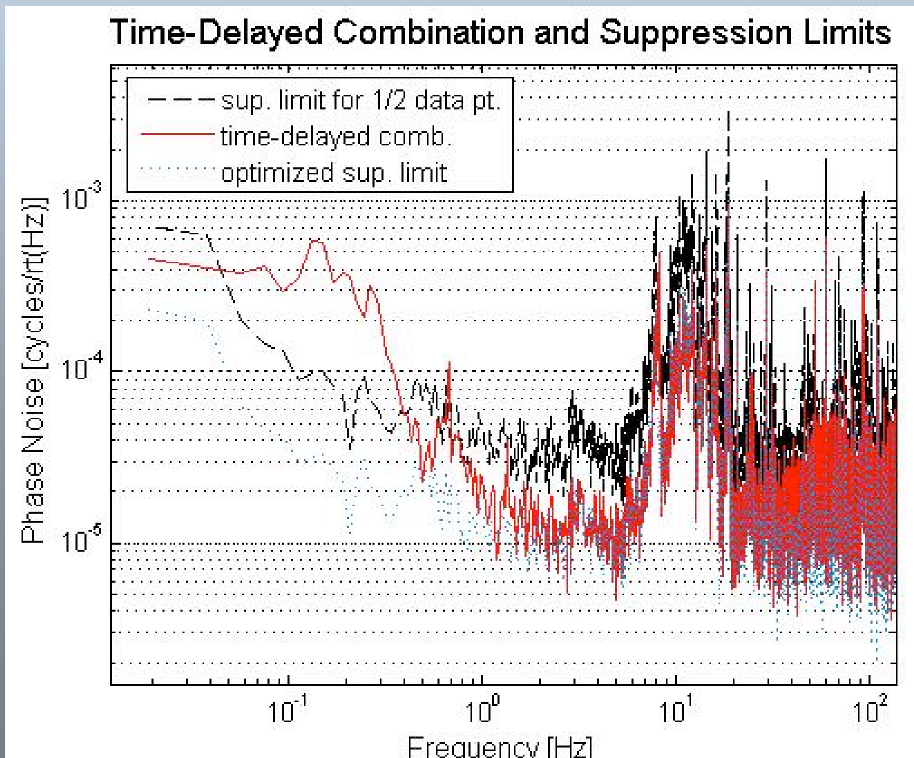


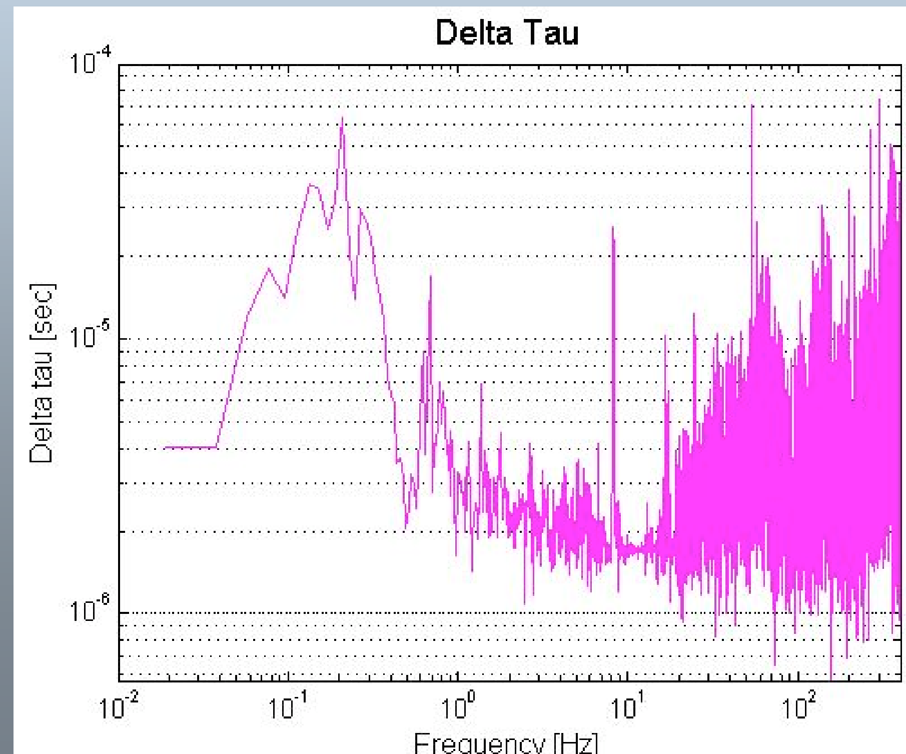


Timing Resolution Suppression Limit & Timing Error

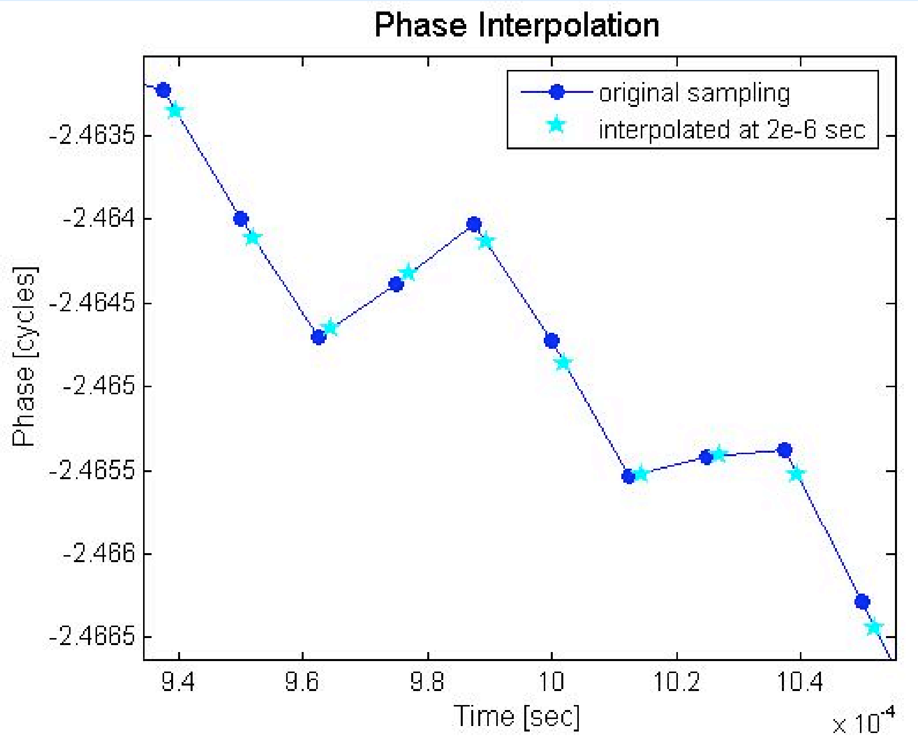
$$|\widetilde{S}(f)| = 2\sin(\pi f \Delta\tau)\,|\widetilde{\phi}_p(f)|$$

$$\Delta\tau = \frac{1}{\pi f}\sin^{-1}\left[\frac{|\widetilde{S}(f)|}{2|\widetilde{\phi}_p(f)|}\right]$$



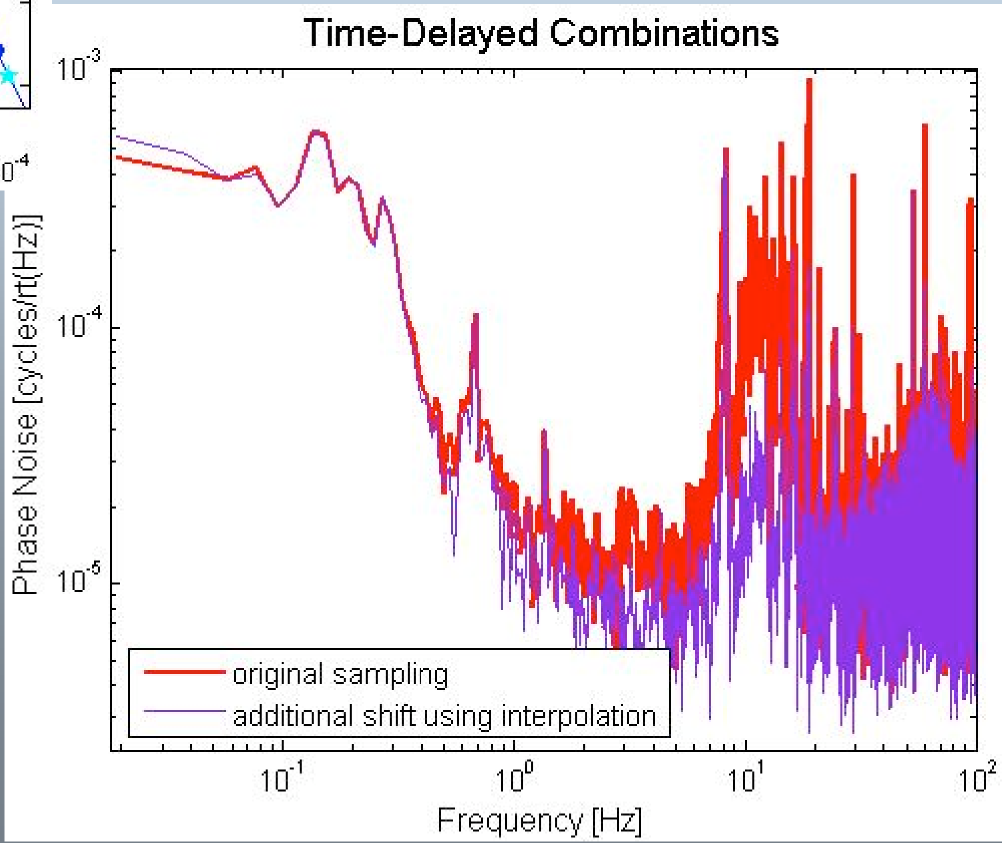


Interpolation

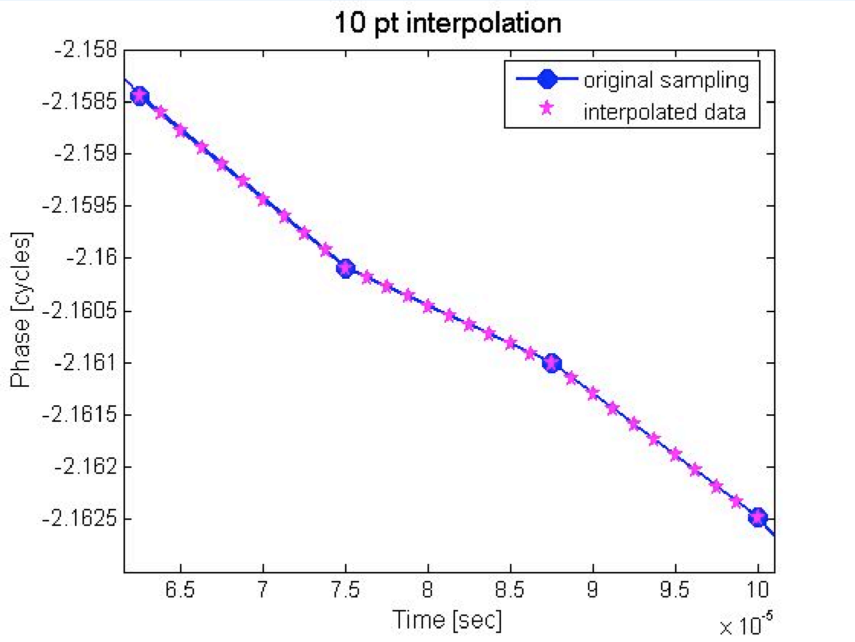


Used linear interpolation to shift one data set 2 _sec

2.0005625 +
0.000002 =
2.0005645 sec

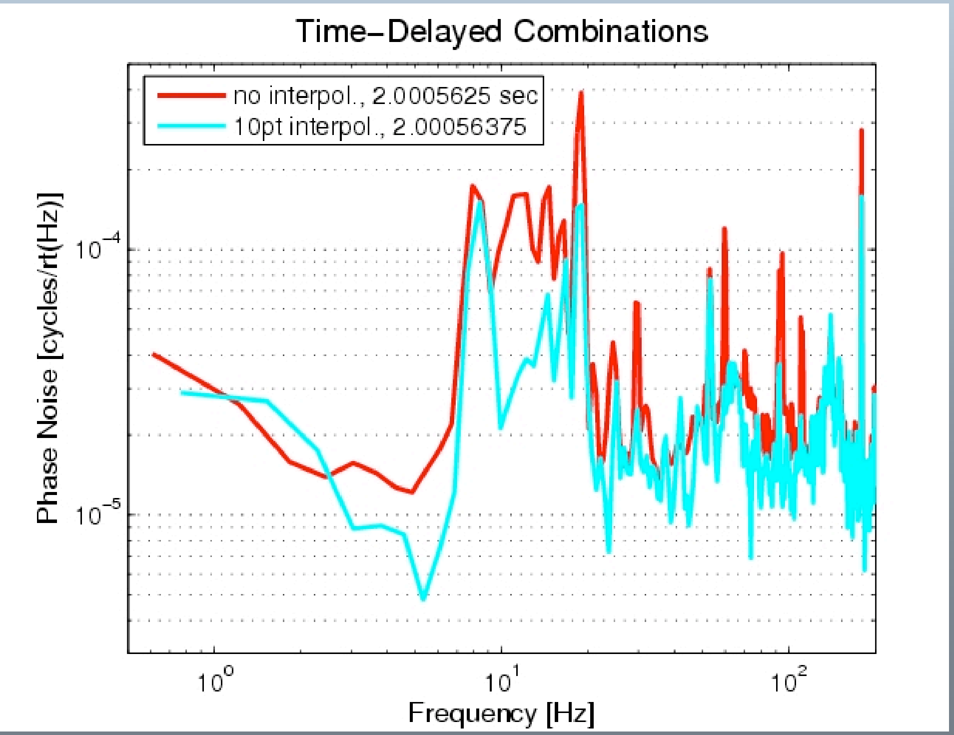


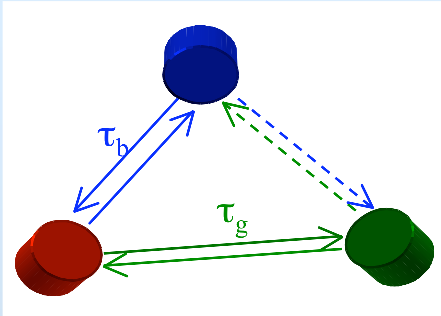
10-pt Interpolation



10-pt interpolation gives 1.25 _sec resolution

The optimal shift of 2.00056375 sec is the closest value to the previous estimate of 2.00056425 sec.





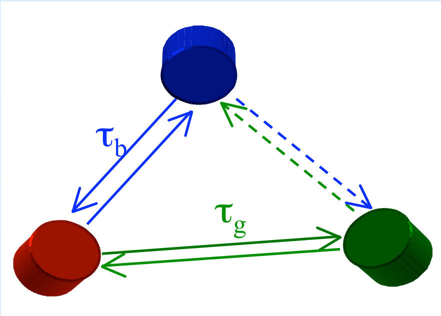
$$S_b(t) = -2\omega_0\tau_b - \phi(t) + \phi(t-2\tau_b) + h_b(t) + h_b(t-\tau_b)$$

$$S_g(t) = -2\omega_0\tau_g - \phi(t) + \phi(t-2\tau_g) + h_g(t) + h_g(t-\tau_g)$$

Instead of combining $S_b(t)$-$S_g(t)$, use $S_b(t)$ - $S_g(t)$ - $S_b(t\text{- }2\_{}_g)$ + $S_g(t\text{- }2\_{}_b)$

$S_b(t)$:	$-2\_{}_0\_{}_b$	-_(t)	$\_(t\text{-}2\_{}_b)$		$h_b(t)+h_b(t\text{-}\_{}_b)$
$-S_g(t)$:	$2\_{}_0\_{}_g$	_(t)	$\text{-}\_(t\text{-}2\_{}_g)$		$\text{-}h_g(t)\text{-}h_g(t\text{-}\_{}_g)$
$-S_b(t\text{-}2\_{}_g)$:	$2\_{}_0\_{}_b$		$\_(t\text{-}2\_{}_g)$	$\text{-}\_(t\text{-}2\_{}_b\text{-}2\_{}_g)$	$\text{-}h_b(t\text{-}2\_{}_g)\text{-}h_b(t\text{-}\_{}_b\text{-}2\_{}_g)$
$S_g(t\text{-}2\_{}_b)$:	$-2\_{}_0\_{}_g$		$\text{-}\_(t\text{-}2\_{}_b)$	$\_(t\text{-}2\_{}_b\text{-}2\_{}_g)$	$h_g(t\text{-}2\_{}_b)+h_g(t\text{-}2\_{}_b\text{-}\_{}_g)$

Second Generation TDI compensates for effects due to space craft motion with additional terms.



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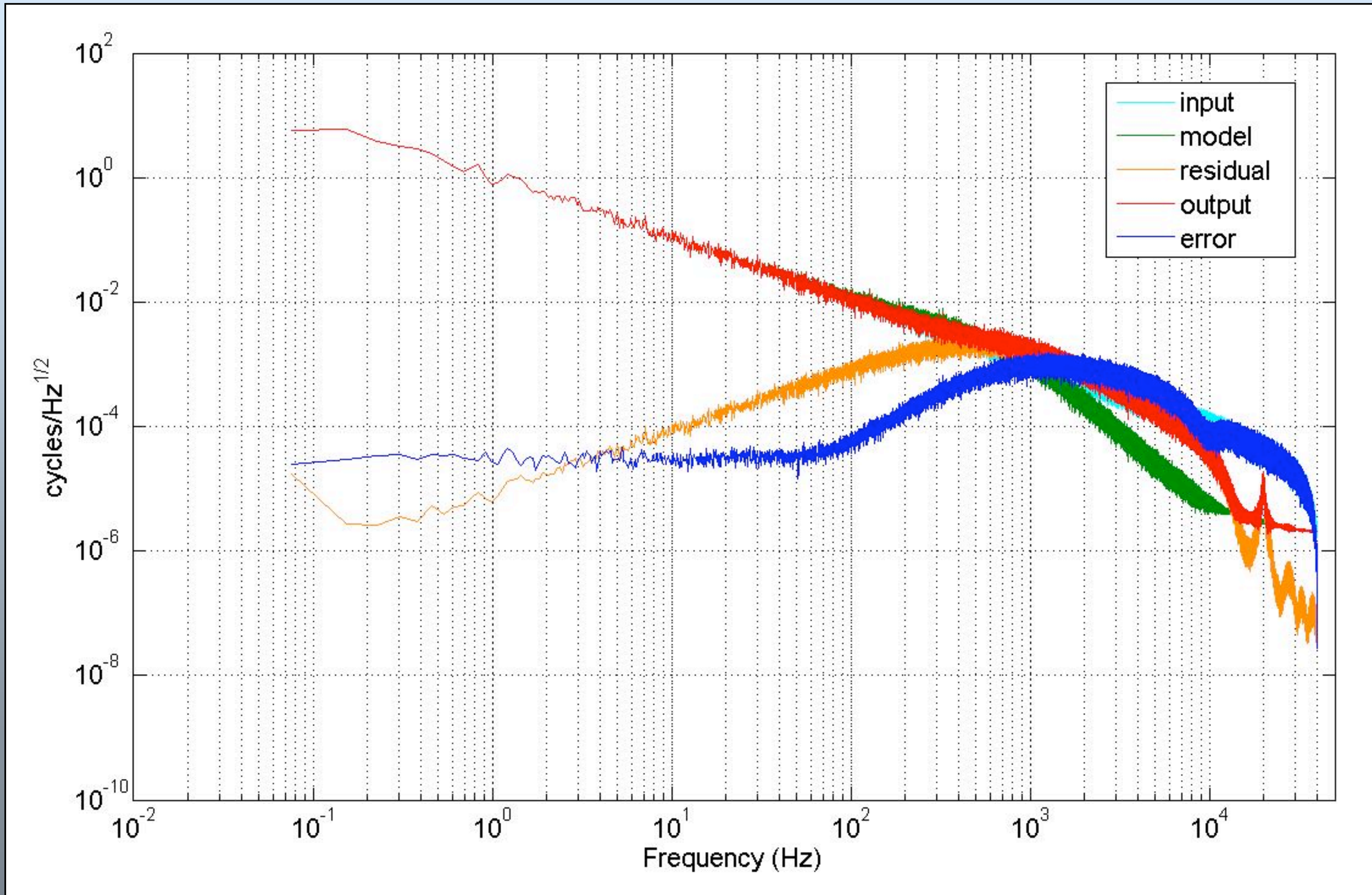
$-S_g(t)$:	$2\_{}_0\_{}_g$	$\_(t)$	$-\_(t-2\_{}_g)$		$-h_g(t)-h_g(t-\_{}_g)$
$-S_b(t-2\_{}_g)$:	$2\_{}_0\_{}_b$		$\_(t-2\_{}_g)$	$-\_(t-2\_{}_b-2\_{}_g)$	$-h_b(t-2\_{}_g)-h_b(t-\_{}_b-2\_{}_g)$
$S_g(t-2\_{}_b)$:	$-2\_{}_0\_{}_g$		$-\_(t-2\_{}_b)$	$\_(t-2\_{}_b-2\_{}_g)$	$h_g(t-2\_{}_b)+h_g(t-2\_{}_b-\_{}_g)$

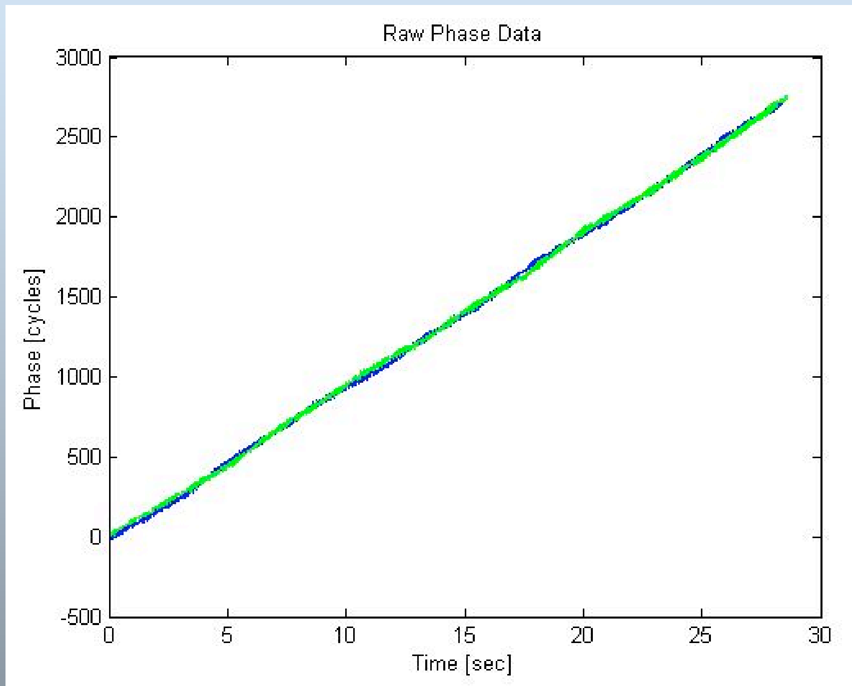
All terms cancel except for those due to the change in phase from a gravitational wave!

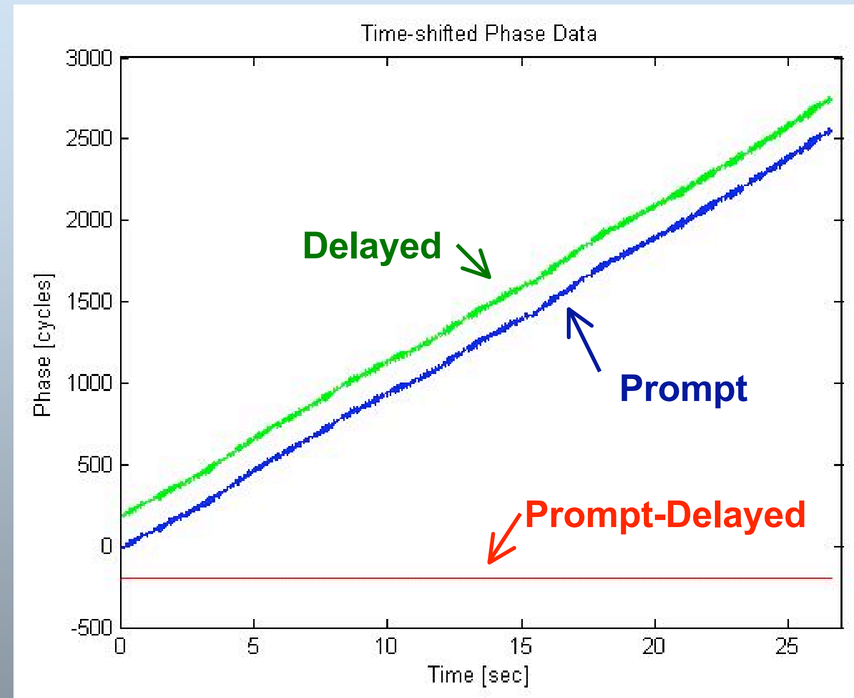
Second Generation TDI compensates for effects due to space craft motion with additional terms.

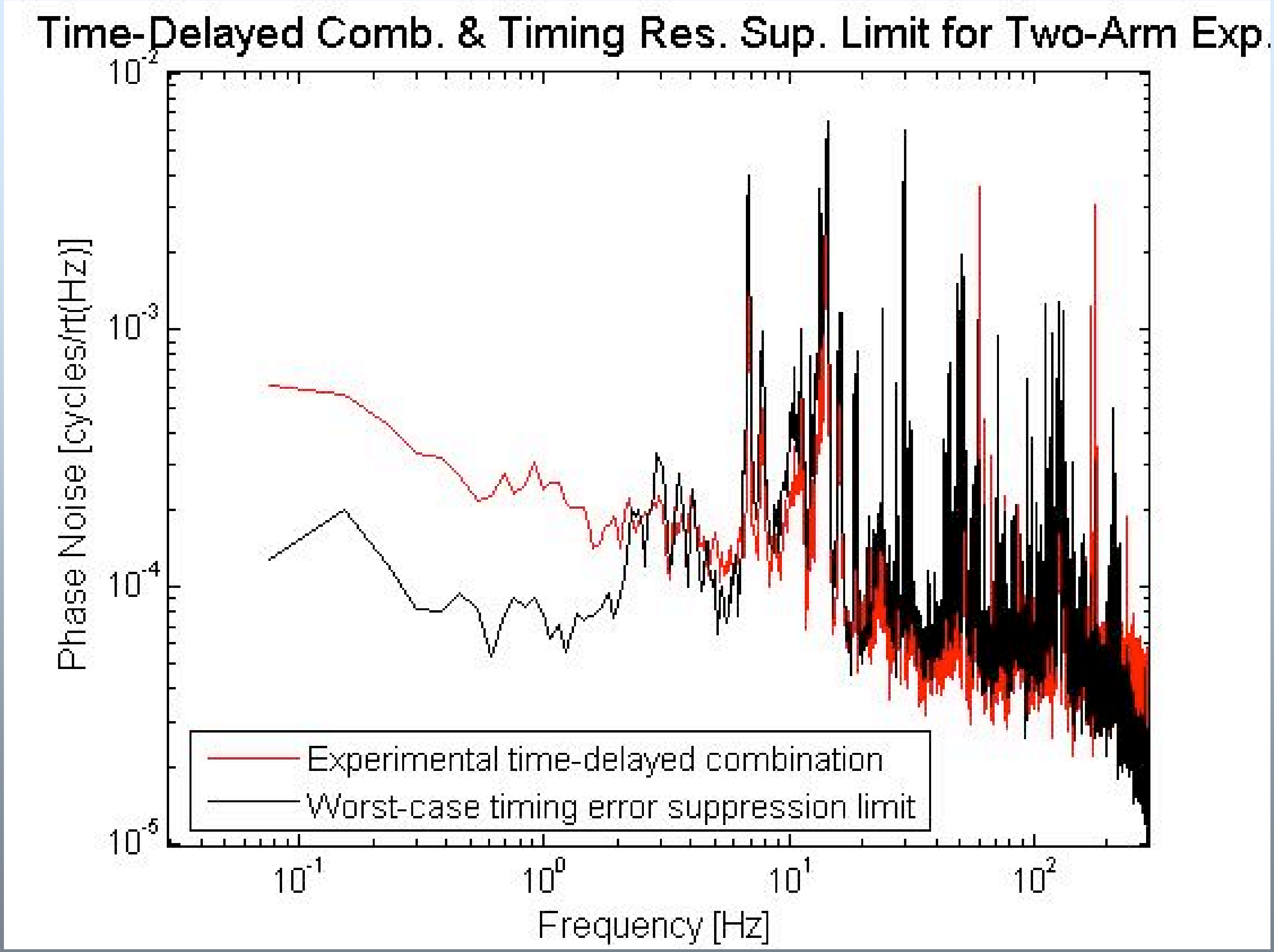
Modeled Performance of Post-Process Phasemeter



Initial Optical Experiment






Time-Delayed Comb. & Timing Res. Sup. Limit for Two-Arm Exp.
Phase Noise [cycles/rt(Hz)]
Frequency [Hz]
Experimental time-delayed combination
Worst-case timing error suppression limit